TRANSACTIONS OF THE AMERICAN CLINICAL AND CLIMATOLOGICAL ASSOCIATION, VOL. 115, 2004

IMPLICATIONS OF ABRUPT CLIMATE CHANGE

RICHARD B. ALLEY

UNIVERSITY PARK, PENNSYLVANIA

ABSTRACT

Records of past climates contained in ice cores, ocean sediments, and other archives show that large, abrupt, widespread climate changes have occurred repeatedly in the past. These changes were especially prominent during the cooling into and warming out of the last ice age, but persisted into the modern warm interval. Changes have especially affected water availability in warm regions and temperature in cold regions, but have affected almost all climatic variables across much or all of the Earth. Impacts of climate changes are smaller if the changes are slower or more-expected. The rapidity of abrupt climate changes, together with the difficulty of predicting such changes, means that impacts on the health of humans, economies and ecosystems will be larger if abrupt climate changes occur. Most projections of future climate include only gradual changes, whereas paleoclimatic data plus models indicate that abrupt changes remain possible; thus, policy is being made based on a view of the future that may be optimistic.

INTRODUCTION

Climate change is one of the many challenges faced by humans in preserving and improving our lives and future. Several groups issue climate-change projections, but the most widely used are those of the Intergovernmental Panel on Climate Change (IPCC) (1,2). This is an international body, involving scientists, policymakers, nongovernmental and governmental groups, and more, that seeks to provide the scientific basis for assessing future climate changes and the likely impacts of those changes. The focus of the IPCC is primarily on human-caused as opposed to natural changes.

The IPCC summarized extensive data showing that the composition of the Earth's atmosphere is being changed in many ways by humans, with prominent increases in carbon dioxide, methane, and other "greenhouse gases" that warm the Earth's surface by intercepting

Department of Geosciences and EMS Environment Institute, Pennsylvania State University, Deike Building, University Park, PA 16802, USA Ph. 814-863-1700, Fax 814-863.7823 Email ralley@essc.psu.edu

some outgoing thermal radiation. With high confidence, the increase in greenhouse gases has contributed to globally averaged warming over the most recent decades.

If the greenhouse-gas loading of the atmosphere were stabilized at current levels, warming likely would continue for some time. This is because some heat from the atmosphere now is being transferred to warm the oceans and land surface and to melt ice. As these parts of the climate system come to equilibrium, more heat will be left in the atmosphere. Additional increase in greenhouse gases will increase the expected warming further.

Greenhouse warming in turn is expected to cause many changes. These include: globally averaged increase in precipitation but summertime drying of modern grain belts; increase in instances of extreme heat; warming of polar regions more than the tropics; warming of nights more than days; poleward and upward migration of many species including disease-bearing organisms; sea-level rise; and more.

Impacts of human-caused climatic changes are expected to cause the largest difficulties for poor people, who often lack extensive resources to deal with changes, and who are tightly tied to local conditions through hunter-gatherer or agricultural activities. Sea-level changes will stress coastal peoples. Among ecosystems, those that are isolated and thus face difficulty in migrating as climate changes, and those dominated by long-lived and slowly reproducing species, are especially at risk.

Impacts of changes are clearly larger if those changes are more rapid and less expected (3,4). If humans know a change is coming, and have time to prepare for that change, many of the negative impacts can be minimized or even avoided entirely. For example, as I am writing this during late August, 2003, press reports indicate that the French government has just estimated that more than 11,000 people were killed by a heat wave this summer; however, in neighboring Portugal even higher temperatures produced a much lower death toll, presumably because Portugal is more accustomed to and more prepared for the effects of such heat.

Perhaps because IPCC projections for planners involve gradual changes, most outlooks for the impacts of global warming indicate that problems will be challenging but surmountable. Economically optimal human behavior in the near future would involve some effort to reduce greenhouse-gas emissions, but not a huge effort (5,6).

Recent findings on abrupt climate change may affect this calculation, however. Large, rapid, and widespread climate shifts have occurred in the past and may occur in the future. If they occur, such changes will increase the costs and other impacts of climate change, and may require recalculation of optimal behavior. Here, I briefly review the evidence for the occurrence and possible recurrence of abrupt climate changes, potential impacts, and suggestions for responses.

MATERIALS AND METHODS

Reliable climate records from instruments span a surprisingly short interval of time. Perhaps the longest continuous instrumental temperature record extends back only to about the year 1659 (7), and applies only to central England. Somewhat longer records are available from written records of climate-related variables, such as droughts, floods, sea-ice extent and more. Longer climate records require the analysis of sedimentary archives.

On land, sediments accumulate only in special places, including in lakes and bogs, and on glaciers and ice sheets; most of the land surface is being eroded and so is not building a long sedimentary record. Sediments accumulate almost everywhere on the sea bottom. Many characteristics of sediments are affected by climate, allowing sediment characteristics to be used to infer past climatic conditions. Ages of the sediments can be learned in various ways, allowing production of complete histories (e.g., 8–10).

For example, in seasonal climates, a tree produces one identifiable ring per year, and the age of the tree can be estimated from layer counting. In a "good" year, the tree forms a thicker ring. In an especially cold region, a "good" year will be a warm one, and so the history of tree growth in the rings can be used to identify warm times. If the tree is in a dry region, a "good" year is a wet one, and allows reconstruction of water availability. The pattern of good and bad years can be matched between living trees and nearby dead trees ("subfossil wood") if sufficient time overlap is available, allowing extension of the record. The longest continuous such record now extends beyond 10,000 years (11). Much older wood exists and is being studied, but without the continuous tie of layers to the present.

Many species are sensitive to climate, and leave shells or leaves or pollen or other material in sedimentary deposits. A sediment core that contains pollen, etc. in recent layers primarily from species adapted to warm climates, but materials from tundra plants in older layers, indicates that a large warming occurred in the past. Dating is possible by various techniques, including measurements of radiometric decay, counting of annual layers, and other ways (9).

For example, offshore of Venezuela, trade winds during northern winters mix the waters of the Cariaco Basin, bringing nutrients to the surface to fertilize blooms of plankton. The white shells of the plankton settle quickly to the sea floor, making a white layer. Lack of oxygen in the deep waters of this silled basin restricts burrowing organisms, so the layer is preserved. As the summer approaches, the trade winds follow the sun north and the basin comes under the influence of the strong rains at the meteorological equator (the Intertropical Convergence Zone or ITCZ). This suppresses oceanic productivity but washes dark mud into the ocean. Hence, a year produces a couplet of dark and light layers, which can be counted (12,13). Thickness of layers, pollen in the layers, composition of species, and other indicators reveal climate over time (e.g., 14).

Ice cores have proven especially useful in reconstructing past climates (e.g., 15,16). Glaciers and ice sheets are true atmospheric sediments, and the materials in them have not been altered in a lake or ocean before deposition. Many glaciers and ice sheets, although not all, accumulated sufficiently rapidly that annual layers can be counted. (If typical snow drifts are similar to or higher than the typical thickness of a year's accumulation, annual layers will not be preserved.) Annual layers are recognizable through physical changes caused in near-surface snow by sunlight, and by other annual oscillations in isotopic or chemical indicators (17). The accuracy of the dating can be checked by chemically identifying the volcanic ash from historically dated volcanic eruptions (18), and is typically quite good (zero-error dates have been produced, and errors of only one year in one-hundred are often fairly easy to obtain).

The thickness of an annual layer (after correction for the effects of snow compaction and glacier flow) provides an estimate of past snow accumulation rate on the ice sheet. The concentration of wind-blown materials (sea salt, continental dust, forest-fire smoke, pollen, volcanic ash, extraterrestrial dust, etc.) reveals much about sources and transport, after correction for the changing dilution caused by changing snow accumulation rate. Chemical and isotopic fingerprints of wind-blown materials may allow them to be related to unique sources. The transformation of snow to ice traps bubbles that are high-fidelity recorders of past atmospheric compositions. Especially of interest are carbon-dioxide concentrations, because of greenhouse effects on surface temperature, and methane concentrations, which affected surface temperature and which record the extent of the wetlands giving rise to the methane. Several indicators, including the isotopic composition of the water in the ice, reveal past temperatures on the ice sheet. Thus, a rather complete picture of climate on an ice sheet and in broad regions elsewhere can be assembled from a single ice core.

RESULTS

Paleoclimatic research has provided insights on numerous aspects of climate change. Changes have occurred on many time scales, in response to many forcings. Important changes have occurred over:

→Billions of years, in response to brightening of the sun (19,20), and in response to biological effects on atmospheric composition such as the rise of oxygen;

→Hundreds of millions of years, in response to drifting continents affecting oceanic and atmospheric currents, and affecting the rate at which volcanoes return to the atmosphere the carbon dioxide removed by chemical reactions with rocks (21);

→Tens to hundreds of thousands of years, in response to variations in Earth's orbit that affect the seasonality of energy receipt from sunshine at different latitudes (the Milankovitch mechanism; e.g. 22,23);

→Eleven, twenty-two, and eighty-eight years, in response to solar variations linked to the sunspot cycle (e.g., 24);

→Three to five years, in response to the El Niño/Southern Oscillation in the Pacific Ocean (e.g., 25,26).

Other intervals and causes could be listed as well, including the annual and daily changes that are so familiar, the occasional effects of large volcanic eruptions, and the much-less-frequent occasional effects of impacts of extraterrestrial bodies. Notice, however, that the changes over hundreds of millions of years or longer are so slow that they can be considered unchanging for the human time scales we usually consider. The daily and annual cycles are huge, but fast enough that we do not count them in climate, but in weather. The sunspot cycles are evident in climate records, but very weak, and do not explain most of the climate variability we observe. A large volcanic eruption can lower global average temperature by a degree or so for a year or two (e.g., 24), but there is no evidence of sufficient organization or clustering of such eruptions to have a larger and longer-lasting influence on climate (and there is much evidence against such organization or clustering). Evidence of changes in Earth's magnetic field is available from ice cores and other sources (a weaker magnetic field allows stronger penetration of cosmic rays into the atmosphere, producing more beryllium-10 and other species that are quickly precipitated to the surface; 27), but large climate changes are not associated with the magnetic-field changes, indicating that the magnetic field is not playing a large role in the climate system.

Perhaps the strongest result to emerge from the available paleoclimatic data is the importance of carbon-dioxide concentration in determining warmth. The warm world of the dinosaurs 100 million years ago, which lacked permanent ice, occurred when carbon dioxide is estimated to have been high (28,29). The growth of ice first on Antarctica and then in the north accompanied a long-term drop in carbon dioxide (30). The orbital variations that have paced the ice ages of the last hundreds of thousands of years produced north-south asymmetry in forcing (more sunshine in the north occurs with less sunshine in the south from some of the orbital features), yet the ice ages were globally synchronous. The only plausible explanations for this behavior involve the effects of carbon dioxide; as northern sunshine dropped and ice grew, carbon dioxide fell for poorly understood reasons, controlling southern temperatures (Figure 1) (e.g., 31). Models forced with the reconstructed variations of carbon dioxide typically show considerable skill in simulating the climate changes that occurred, whereas the same models forced with other known forcings but not carbon dioxide changes lack that skill (reviewed by 32).

Of greater import here is that recent ice-core data confirmed earlier studies that there have been millennial-spaced climate changes (Figure 2). These have been large (1/3 to 1/2 of the entire difference between the climates of the recent and ice-age worlds), widespread (affecting much or all of the Earth's surface), and persistent (staying in one climate state for centuries before switching to a different state). Coolings have been large and abrupt, and warmings more so, locally reaching 10 degrees C or more in a decade or so (33,34).

The existence of these abrupt climate changes is somewhat alarming. Most of them occurred during the cooling into and warming out of ice ages, when average temperatures were lower and more land ice existed on Earth than now. However, one at least punctuated a time somewhat warmer than the last century or so in many records, so warmth provides no guarantee of stability (35,36).

The general anomaly pattern associated with the main abrupt jumps in the ice-age world and into more recent times includes cold conditions across the high northern latitudes and especially around Greenland and northwestern Europe, dry and windy conditions in many places including the monsoonal belts of Asia and Africa, and slightly warm conditions in the far southern Atlantic and most of Antarctica (37,38). Oceanic circulation was changed as well, especially in the north Atlantic (39–42).

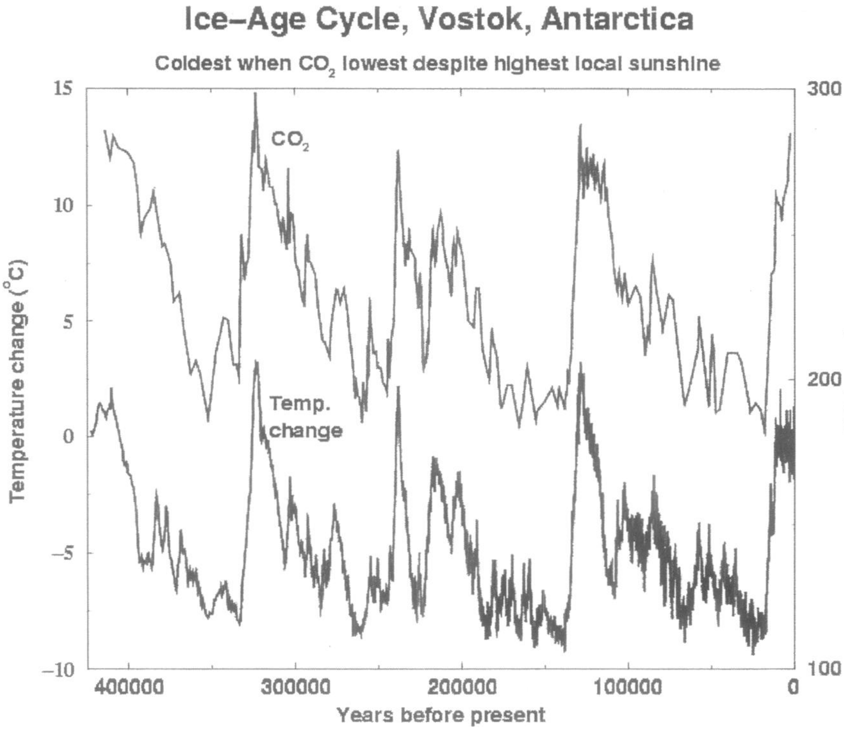

FIG. 1. History of atmospheric carbon-dioxide concentration derived from concentrations in bubbles trapped in the Vostok, East Antarctica ice core (top) and of temperature in East Antarctica derived from the isotopic composition of the ice core, following (52). The very strong similarities are evident. More striking is that the coldest times typically correspond to local maxima, not minima, in midsummer sunshine, as explained in (31) and other sources. Plausible explanations of this odd behavior in the temperature history all involve the carbon-dioxide history.

In the modern world, Atlantic waters are saltier hence denser than equivalent Pacific waters, probably because the trade winds blowing across central America take water evaporated from the Atlantic to rain on the Pacific. Cooling of salty waters in the north Atlantic causes water sinking before freezing, allowing additional warm water to flow northward and maintain warmth in the region around and downwind of the north Atlantic, with little sea ice (39–42). The leading hypothesis for the abrupt changes of the past is that freshening of the north Atlantic surface (from surges of ice sheets from the land, outburst flooding from ice-dammed lakes, or other causes) allowed north Atlantic freezing before sinking, producing cold northern conditions. However, this slowed or stopped the northward cross-equatorial flow and

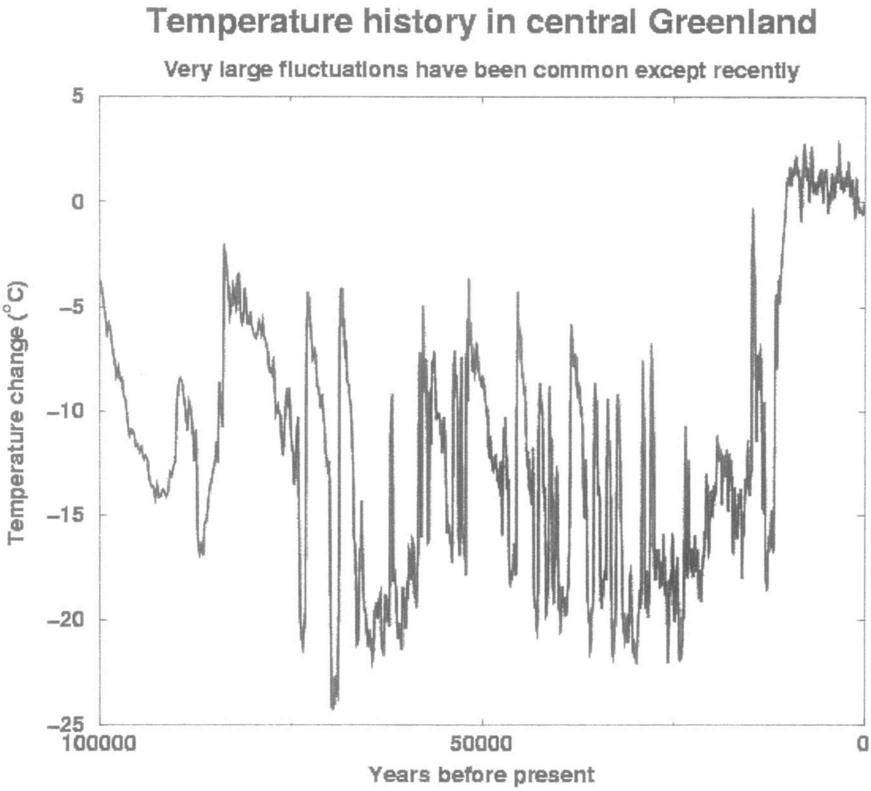

FIG. 2. History of temperature in central Greenland, following (53).

thus allowed southern warming. Continued atmospheric moisture export from the Atlantic to the Pacific was then not balanced by export of the remaining salt in the waters that sank in the north Atlantic and then circulated southward in the deep Atlantic, around the Antarctic, and north into the Pacific. The resulting salinity increase in the Atlantic eventually increased the Atlantic surface-water density enough to restart the northern sinking, producing a strong northern warming. Switches in storm tracks and other features of the atmosphere-ocean system then explain the other climate anomalies.

Models of the Earth system, when driven by north Atlantic freshening, accurately simulate many aspects of the climate anomalies associated with the abrupt, millennial-spacing changes of the past (e.g., 43–46). However, there is a tendency for the models to simulate somewhat smaller and less-extensive changes than reconstructed from paleoclimatic indicators, suggesting either that other causes were involved, or that the models are undersensitive. Importantly, for the ice-age events, and for the large event and many smaller events during the current warm period, cooling of the north Atlantic led to drying in monsoonal regions of Africa and Asia (47–49).

DISCUSSION

The realization that abrupt climate changes exist, and have occurred repeatedly in the past across broad regions, has stimulated much research and evaluation. The recent report of the U.S. National Research Council (3) advanced two related definitions of abrupt climate change: that the change occurs faster than the cause; and, that the change is sufficiently large, rapid and widespread to cause economies or ecosystems to have difficulty adapting.

Abrupt climate changes are believed to occur when the climate system crosses some threshold (either through forcing from outside, or from unforced variability). Evolution then occurs to a new state, at a rate determined by the climate system and not by the forcing. Such threshold behavior is also observed in canoes—lean a little and the canoe leans a little with you, in a gradual change akin to those considered by the IPCC (1,2). Lean a little more, and the canoe flips over, at a rate much faster than your original leaning.

The north Atlantic is one region where threshold behavior can exist. Sufficient freshening can switch from a sinking to a freezing behavior there, and the switch is quite abrupt in at least some models. Droughts on land surfaces also can exhibit threshold behavior. Because much of the rainfall of continental interiors is recycled evaporation from plants, loss of plant growth in a drought can allow water to flow down streams rather than being captured by roots, reducing additional rainfall and reinforcing the drought. Another threshold behavior in the climate system involves water penetration into crevasses triggering a break-up of an ice shelf around Antarctica, allowing faster ice flow and sea-level rise (e.g., 50). Other important thresholds almost certainly exist.

Threshold crossings are quite difficult to predict, and may be chaotic (were predictions easier, fewer people would fall out of canoes). Threshold crossings are more likely when a system is being forced to change (sitting very still in a canoe on a quiet lake is unlikely to trigger a crossing that capsizes a canoe, but a paddler leaning, or waves rising, or other forcings can cross the threshold and capsize the canoe). Hence, humans likely are increasing the probability of a threshold crossing triggering abrupt climate change, not because human forcing is necessarily worse than natural forcing, but simply because we are "rocking the boat".

Some suggestions in the popular literature, e.g., of an abrupt climate change triggering a new ice age, exceed plausible impacts. However, human activities do seem to be freshening the north Atlantic through melting of ice and through increases in snowfall and rainfall at high northern latitudes, and this may cause a weakening or cessation of the modern ocean-circulation pattern. Impacts might include actual cooling around the north Atlantic especially in wintertime (51), and perhaps drying in the monsoon belts where very large populations depend on the seasonal rainfall. The projected drying of grain-belt regions in a warming world appears capable of triggering dust-bowl-type events, with major regional consequences (1,2).

In one sense, knowledge of abrupt climate change does not fundamentally alter the major issue. Humans will have to adapt to changing climates that influence the appropriateness of infrastructure (e.g., air conditioners and snow plows), the distribution of disease-causing organisms, the viability of ecosystems, and the well-being and associated health effects of many people. But, abrupt climate change could cause some counterintuitive effects, such as global warming producing local cooling. This, plus the difficulty of predicting abrupt climate change, may recommend urgency in improving understanding of climate changes and possible impacts, and in improving resiliency and adaptability of economies and ecosystems. By building flexibility into infrastructure, and preparing "what if" scenarios, it may be possible to make responses to abrupt climate changes more efficient and faster, thus improving future health and well-being.

CONCLUSIONS

The Earth has experienced abrupt and gradual climate changes in the past, and is highly likely to do so in the future. Human forcing of the climate is emerging from natural variability as the major driver of change (e.g., 1), and will become increasingly important in the future if ongoing human behavior patterns continue. Paleoclimatic evidence shows the strong influence of carbon dioxide on climate, and suggests that future changes will be as large as, or larger than, those now being projected by leading climate scientists.

The earth system in the past has repeatedly crossed thresholds, triggering abrupt climate changes to different and persistent states. Human activity likely is increasing the probability of abrupt changes in the future, by causing forcing that may be nearing threshold crossings.

Predictions of abrupt climate changes will be more difficult to make than of gradual changes. There is no fundamental difference between the possible impacts of abrupt versus gradual climate change. However, because abrupt climate changes, if they occur, will be faster and less anticipated than the gradual changes on which policymakers have previously concentrated, impacts will be larger.

ACKNOWLEDGMENTS

I thank numerous colleagues in the ice-core and abrupt-climate-change communities. Funding was provided by the National Science Foundation Office of Polar Programs, from grants including 0126187, 0087380, 0087160 and 0229609.

REFERENCES

1. Intergovernmental Panel on Climate Change. 2001. *Climate Change 2001: The Science of Climate Change. Report of Working Group I.* Cambridge University Press, UK. Available online at: http://www.usgcrp.gov/ipcc
2. Intergovernmental Panel on Climate Change. 2001. *Climate Change 2001: Impacts, Adaptation, and Vulnerability. Report of Working Group II.* Cambridge University Press, UK. Available online at: http://www.usgcrp.gov/ipcc
3. National Research Council. 2002. *Abrupt Climate Change: Inevitable Surprises.* National Academy Press, Washington, DC, U.S.A., 230 pp.
4. Alley, R.B., J. Marotzke, W.D. Nordhaus, J.T. Overpeck, D.M. Peteet, R.A. Pielke, Jr., R.T. Pierrehumbert, P.B. Rhines, T.F. Stocker, L.D. Talley, and J.M. Wallace. Abrupt climate change. *Science* 299, 2005–2010.
5. Nordhaus, W.D. 1994. *Managing the Global Commons: The Economics of Climate Change.* Massachusetts Institute of Technology Press, Cambridge, MA, U.S.A.
6. Nordhaus, W.D. and J. Boyer. 2000. *Warming the World: Economic Modeling of Global Warming.* Massachusetts Institute of Technology Press, Cambridge, MA, U.S.A.
7. Jones, P.D. and R.S. Bradley. 1992. Climatic variations over the last 500 years. pp. 649–665, in R.S. Bradley and P.D. Jones, eds., *Climate Since A.D. 1500.* Routledge, London.
8. Crowley, T.J. and G.R. North. 1991. *Paleoclimatology.* Oxford University Press, Oxford, UK.
9. Bradley, R.S. 1999. *Paleoclimatology: reconstructing climates of the Quaternary, 2nd ed.* Academic Press, San Diego, CA, U.S.A. 613 pp.
10. Cronin, R.M. 1999. *Principles of Paleoclimatology.* Columbia University Press, NY, U.S.A. 560 pp.
11. Becker, B., B. Kromer and P. Trimborn. 1991. A stable-isotope tree-ring timescale of the late glacial/Holocene boundary. *Nature* 353, 647–649.
12. Hughen, K.A., J.T. Overpeck, L.C. Peterson and S. Trumbore. 1996. Rapid climate changes in the tropical Atlantic region during the last deglaciation. *Nature* 380, 51–54.
13. Hughen, K.A., J.T. Overpeck, S.J. Lehman, M. Kashgarian, J. Southon, L.C. Peterson, R. Alley and D.M. Sigman. 1998. Deglacial changes in ocean circulation from an extended radiocarbon calibration. *Nature* 391, 65–68.
14. Haug, G.H., K.A. Hughen, D.M. Sigman, L.C. Peterson and U. Rohl. 2001. Southward migration of the intertropical convergence zone through the Holocene. *Science* 293, 1304–1308.

15. Alley, R.B. and M.L. Bender, 1998. Greenland ice cores: Frozen in time. *Scientific American* 278, 80–85.
16. Taylor, K. 1999. Rapid Climate Change. *American Scientist* 87, 320–327.
17. Alley, R.B., C.A. Shuman, D.A. Meese, A.J. Gow, K.C. Taylor, K.M. Cuffey, J.J. Fitzpatrick, P.M. Grootes, G.A. Zielinski, M. Ram, G. Spinelli and B. Elder. 1997. Visual-stratigraphic dating of the GISP2 ice core: Basis, reproducibility, and application. Journal of Geophysical Research 102(C12), 26,367–26,381.
18. Zielinski, G.A., P.A. Mayewski, L.D. Meeker, K. Gronvold, M.S. Germani, S. Whitlow, M.S. Twickler and K. Taylor. 1997. *Journal of Geophysical Research* 102(C12), 26,625–26,640.
19. Kasting, J.F. 1989. Long-term stability of the Earth's climate *Palaeogeography, Palaeoclimatology, Palaeoecology (Global & Planetary Change Section)* 75, p. 83–95.
20. Kasting, J.F. and D.H. Grinspoon. 1991. The faint young Sun problem, In: *The Sun in time*, C.P Sonnett ed., University of Arizona Press, p. 447–462.
21. Walker, J.C.G., P.B. Hays and J.F. Kasting. 1981. A negative feedback mechanism for the long-term stabilization of Earth's surface temperature. *Journal of Geophysical Research* 86(C10), p. 9776–9782.
22. Imbrie, J. and K. Palmer Imbrie. 1979. *Ice ages: solving the mystery*, Enslow Publishers, Hillside, NJ, U.S.A. 224 pp.
23. Imbrie, J., A. Berger, E.A. Boyle, S.C. Clemens, A. Duffy, W.R. Howard, G. Kukla, J. Kutzbach, D.G. Martinson, A. McIntyre, A.C. Mix, B. Molfino, J.J. Morley, L.C. Peterson, N.G. Pisias, W.L. Prell, M.E. Raymo, N.J. Shackleton, and J.R. Toggweiler. 1993. On the structure and origin of major glaciation cycles: 2. The 100,000-year cycle, *Paleoceanography* 8, 699–735.
24. Stuiver, M., P.M. Grootes and T.F. Braziunas. 1995. The GISP2 $\delta^{18}O$ climate record of the past 16,500 years and the role of the Sun, ocean, and volcanoes. *Quaternary Research* 44, 341–354
25. Enfield, D.B. 1989. El Niño, past and present. *Reviews of Geophysics* 27, 159–187.
26. Philander, S.G. 1990. *El Niño, La Niña, and the Southern Oscillation*. Academic Press, San Diego, CA, U.S.A. 293 pp
27. Finkel, R.C. and K. Nishiizumi. 1997. Beryllium 10 concentrations in the Greenland Ice Sheet Project 2 ice core from 3–40 ka. *Journal of Geophysical Research* 102(C12), 26,699–26,706
28. Barron, E.J., P.J. Fawcett, W.H. Peterson, D. Pollard and S.L. Thompson. 1995. A "simulation" of mid-Cretaceous climate. *Paleoceanography* 10, 953–962.
29. Pearson, P.N., R. W. Ditchfield, J. Singan, K.G. Harcourt-Brown, C.J. Nicholas, R.K. Olsson, N.J. Shackleton and M.A. Hall. 2001. Warm tropical sea surface temperatures in the Late Cretaceous and Eocene epochs. *Nature* 413, 481–487.
30. DeConto, R.M. and D. Pollard. 2003. Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO_2. *Nature* 421, 245–249.
31. Alley, R.B., E.J. Brook and S. Anandakrishnan. 2002. A northern lead in the orbital band: north-south phasing of Ice-Age events. *Quaternary Science Reviews* 21, 431–441.
32. Alley, R.B. 2003. Paleoclimatic insights into future climate challenges. *Philosophical Transactions of the Royal Society of London, Series A*, 361(1810), 1831–1849, 10.1098/rsta.2003.1254.
33. Severinghaus, J.P., T. Sowers, E.J. Brook, R.B. Alley and M.L. Bender. 1998. Timing of abrupt climate change at the end of the Younger Dryas interval from thermally fractionated gases in polar ice. *Nature* 391, 141–146.
34. Lang, C., M. Leuenberger, J. Schwander, S. Johnsen. 1999. 16 degrees C rapid temperature variation in Central Greenland 70,000 years ago. *Science* 286, 934–937.

35. Alley, R.B., P.A. Mayewski, T. Sowers, M. Stuiver, K.C. Taylor and P.U. Clark. 1997. Holocene climatic instability: A prominent, widespread event 8200 years ago. *Geology* 25, 483–486.
36. Barber, D.C., A. Dyke, C. Hillaire-Marcel, A.E. Jennings, J.T. Andrews, M.W. Kerwin, B. Bilodeau, R. McNeely, J. Southon, M.D. Morehead, and J.M. Gagnon. 1999. Forcing of the cold event of 8,200 years ago by catastrophic drainage of Laurentide lakes. *Nature* 400, 344–348.
37. Alley, R.B. and P.U. Clark. 1999. The deglaciation of the northern hemisphere: a global perspective. *Annual Reviews of Earth and Planetary Sciences* 27, 149–182.
38. Clark, P.U., N.G. Pisias, T.F. Stocker and A.J. Weaver. 2002. The role of the thermohaline circulation in abrupt climate change. *Nature* 415, 863–869.
39. Broecker, W.S. 1994. Massive iceberg discharges as triggers for global climate change. *Nature* 372, 421–424.
40. Broecker, W.S. 1995. Chaotic climate. *Scientific American* 273, 44–50.
41. Broecker, W.S. 1997. Thermohaline circulation, the Achilles Heel of our climate system: will man-made CO_2 upset the current balance? *Science* 278, 1582–1588.
42. Broecker, W.S. 1998. Paleocean circulation during the last deglaciation; a bipolar seesaw? *Paleoceanography* 13, 119–121.
43. Fawcett, P.J., A.M. Ágústsdóttir, R.B. Alley and C.A. Shuman. 1997. The Younger Dryas termination and North Atlantic deepwater formation: insights from climate model simulations and Greenland ice core data. *Paleoceanography* 12, 23–38.
44. Manabe, S. and R.J. Stouffer. 1997. Coupled ocean-atmosphere model response to freshwater input: Comparison to Younger Dryas event. *Palecoeanography* 12, 321–336.
45. Renssen, H. 1997. The global response to Younger Dryas boundary conditions in an AGCM simulation. *Climate Dynamics* 13, 587–599.
46. Ágústsdóttir, A.M., R.B. Alley, D. Pollard and W. Peterson. 1999. Ekman transport and upwelling from wind stress from GENESIS climate model experiments with variable North Atlantic heat convergence. *Geophysical Research Letters* 26, 1333–1336.
47. Gasse, F. 2000. Hydrological changes in the African tropics since the Last Glacial Maximum. *Quaternary Science Reviews* 19, 189–211.
48. Wang, Y.J., H. Cheng, R.L. Edwards, Z.S. An, J.Y. Wu, C.C. Shen and J.A. Dorale. 2001. A high-resolution absolute-dated Late Pleistocene monsoon record from Hulu Cave, China. *Science* 294, 2345–2348.
49. Morrill, C., J.T. Overpeck and J.E. Cole. 2003. A synthesis of abrupt changes in the Asian summer monsoon since the last deglaciation. *Holocene* 13, 465–476.
50. Scambos, T.A., C. Hulbe, M. Fahnestock and J. Bohlander. The link between climate warming and break-up of ice shelves in the Antarctic Peninsula. *Journal of Glaciology* 46, 516–530.
51. Vellinga, M. and R.A. Wood. 2002. Global climatic impacts of a collapse of the Atlantic thermohaline circulation. *Climatic Change* 54, 251–267.
52. Petit, J.R., J. Jouzel, D. Raynaud, N.I. Barkov, J.M. Barnola, I. Basile, M. Bender, J. Chappellaz, M. Davis, G. Delaygue, M. Delmotte, V.M. Kotlyakov, M. Legrand, V.Y. Lipenkov, C. Lorius, L. Pepin, C. Ritz, E. Saltzman and M. Stievenard. 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Nature 399, 429–436.
53. Coffey, K.M. and G.D. Clow. 1997. Temperature, accumulation, and ice sheet elevation in central Greenland through the last deglacial transition. *Journal of Geophysical Research* 102, 26383–26396.